

P1-C34

Equation of State and Electron Transport Effects in Exploding Wire Evolution

Stephen E. Rosenthal and Michael P. Desjarlais,
Sandia National Laboratories,
 Kyle R. Cochrane,
Ktech Corporation

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Introduction (1)



The detailed evolution of each exploding wire comprising a cylindrical array determines the energy and power densities ultimately achievable in a z-pinch implosion of the array. Presumably, once the relationship between exploding wire evolution and z-pinch dynamics is understood sufficiently, one could design a z-pinch experiment that would produce the optimum behavior for a given application. Before attempting to learn how exploding wire evolution affects z-pinch behavior it is crucial to be able to accurately model the single exploding wire.

Toward that end we have been doing single-exploding-wire simulations in the z-r plane with the MHD code MACH2 [1] and with Sandia's new code ALEGRA [2]. We have so far limited our study to the radial evolution. Our standard configuration corresponds to recent, well diagnosed exploding aluminum wire experiments from Cornell University [3].

[1] MACH Reference Manual by R. E. Peterkin, Jr. and M. H. Freese, July, 1998. The code must not be distributed without written permission from the Air Force Research Laboratory: Phillips Research Site, Kirtland AFB, NM.

[2] ALEGRA: "User Input and Physics Descriptions - Oct99 Release", Edward A. Boucheron, et. al., SAND99-3012, Sandia National Laboratories, Albuquerque, NM.

[3] "Exploding aluminum wire expansion rate with 1-4.5 kA per wire", D. B. Sinars, T. A. Shelkovenko, S. A. Pikuz, J. B. Greenly, and D. A. Hammer, Physics of Plasmas 7(5), 1555 (May 2000).



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Introduction (2)



Simulations show that **the path in phase space that an exploding wire takes in its evolution from solid metal to high-temperature plasma is quite sensitive to the EOS and conductivity models used.**

We have been guided by comparing the simulations with the Cornell data while maintaining as a constraint the consistency of our models with known EOS and conductivity data [4] from independent experiments and with modern physical descriptions appropriate in the parameter regimes of melt and of the metal-insulator transition [5].

A novel view of exploding wires allows us to see graphically the mutual relations between the EOS and the electrical conductivity during the exploding wire's evolution. A key feature that occurs under certain conditions, as observed in experiments, is the transition to a coronal state (most current flowing through the rapidly-expanding low-density ionized vapor at large radius); a rapid transition coincides with a voltage collapse. We identify important features of the EOS and conductivity that allow corona formation in Aluminum in agreement with the data.

[4] A. W. DeSilva and J. D. Katsouras, "Electrical conductivity of dense copper and aluminum plasmas", Phys. Rev. E 57, 5945 (1998).

[5] M. P. Desjarlais, "Practical Improvements to the Lee-More Conductivity Near the Metal-Insulator Transition", Contrib. Plasma Phys., 41, 267 (2001).



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MHD Simulations of Single Exploding Wire



Summary

- The goal is to demonstrate **accurate MHD modeling of a single exploding Al wire** as a precursor to being able to model a wire array.
 - This problem provides a prime benchmark opportunity for our ASCI rad-MHD code ALEGRA
 - We have the advantage of high-quality laboratory measurements from exploding-wire experiments done at Cornell University
- Exploding wire simulations identify regions where our transport models must be most accurate. Improvements we make in these regions (e.g., solid density near melt, and the metal-insulator transition) are critical for achieving the above goal.



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MACH - Brief Description



- developed by the Air Force Research Laboratory: Phillips Research Site, written by Mike Frese, Bob Peterkin, and Tony Giancola.
- ALE (Arbitrary Lagrangian-Eulerian), allows the grid to move independently of the magnetofluid.
- includes diffusion, Lagrangian hydrodynamics, and advection
- non-equilibrium radiation diffusion (3 temps possible: T_e, T_i, T_r)
- elastic-plastic models
- block structure allows the modeling of complex geometries.
- numerous user-supplied boundary conditions
- New EOS/conductivity/opacity models easily implemented

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ALEGRA - Brief Description



- Developed by Sandia National Laboratories, ALEGRA is an Arbitrary Lagrangian-Eulerian Finite Element Code
 - 1D, 2D, or 3D
 - Emphasizes large distortion and shock propagation problems
- Designed to run on distributed-memory parallel computers
- Utilizes Adaptive Mesh Refinement Techniques
- Physics options
 - Hydrodynamics, Solid dynamics, Structural dynamics
 - MHD, Radiation MHD
 - Opacity, Equation of State, Electron Transport models
 - Elastic plastic, Fracture
- Produces accurate results for numerous problems with known solutions (e.g., impact generated shocks, cold diffusion)

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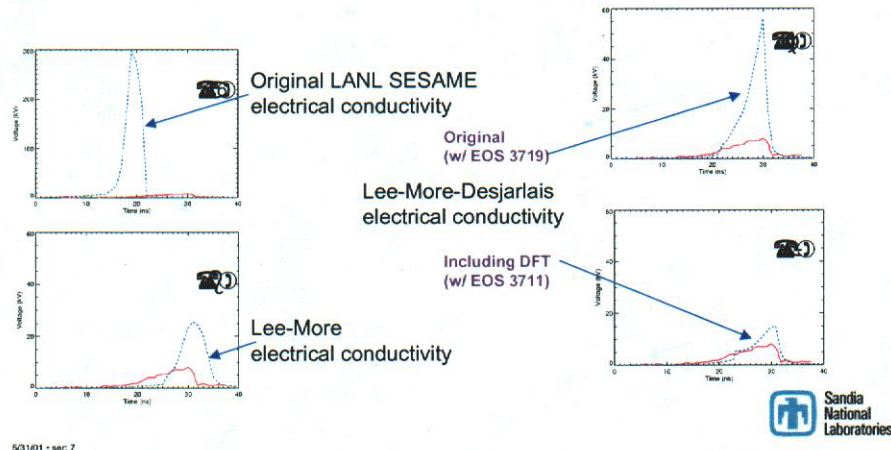


Improving Electron Transport Models and Material Equation Of State Leads to More Accurate Exploding-Wire Simulations

Benchmark RMHD codes, EOS and Transport models against Cornell exploding wire data (e.g., red curves below).

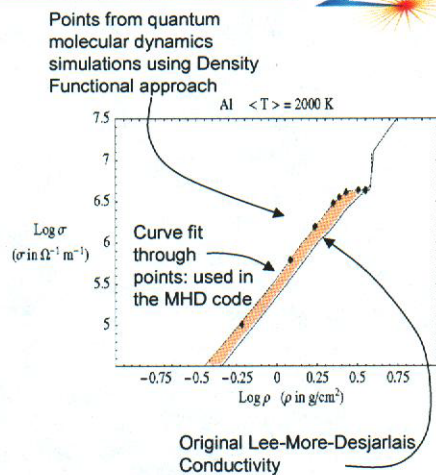


Aluminum



Description of New *Ab Initio* Conductivity Calculations (LMD-DFT)

- This small difference (highlighted in orange) has significant effect on the dynamics of wire heating and expansion.
- Kubo-Greenwood Linear Response formula
- VASP code, Density Functional Theory



Comparison with Measurements



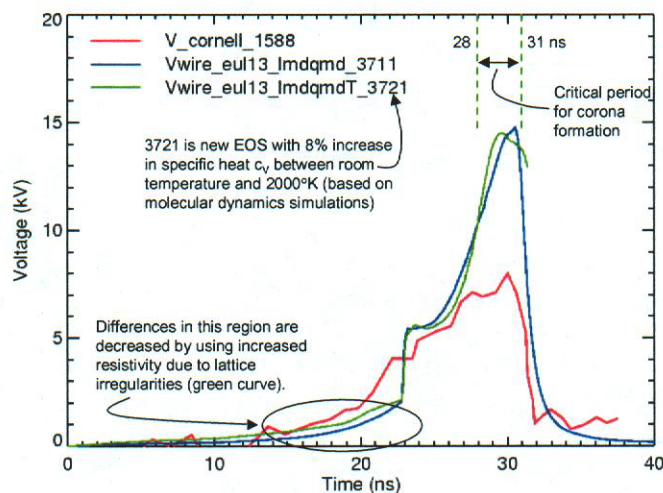
(Simulations are driven by the experimental current waveform)

- **Voltage waveform**
 - Energy deposited in the wire
 - Electrical resistance of wire
- **Expansion velocity of core**



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Comparing Voltage Waveforms: Peak Voltage within Factor of 2, and Accurate Collapse

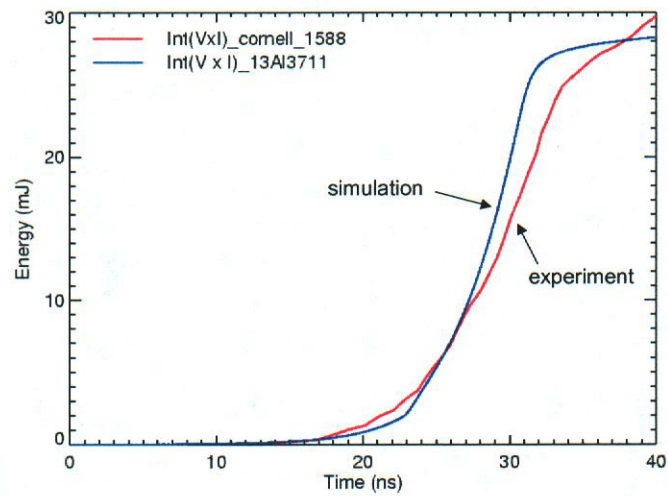


We are continuing to work on improving the EOS and electrical conductivity. As further improvements are incorporated, the remaining small discrepancies in the Voltage might decrease further.



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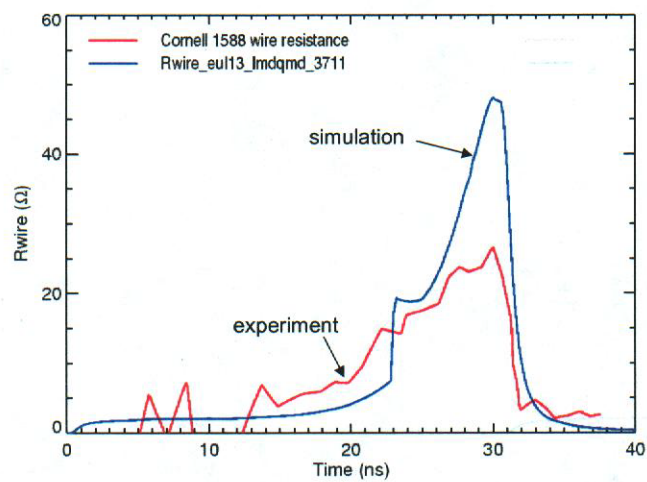
Comparing Energy Waveforms



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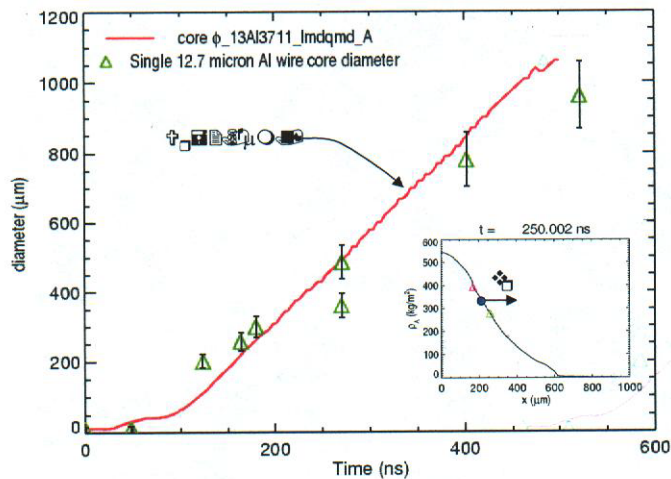
Comparing Wire Resistance Waveforms



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Follow the 50% Density Point to Define the Detectable Diameter of the Wire Core as Measured in Experiment

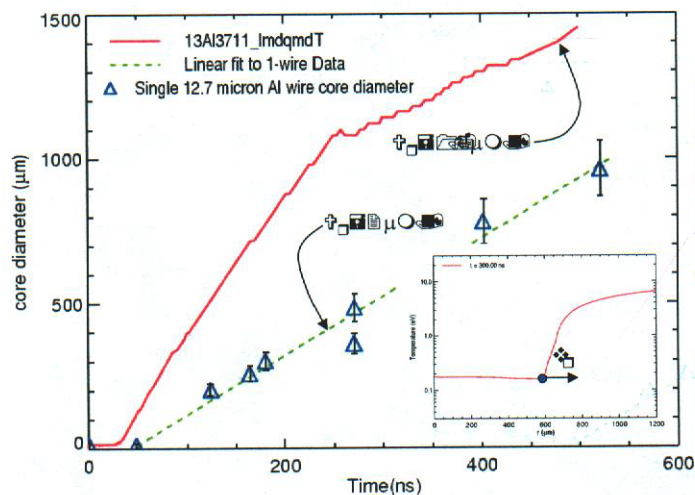


The x-ray backlighter imaging system used in the experiment produces an Abel Transform of the radial density distribution.

We inspect the Abel Transform for the roughly 50% point (taking into account an assumed background noise level of the exposed film, equivalent to 100 kg/m²) to ascertain an expansion velocity in a manner that can be compared to the experiment.



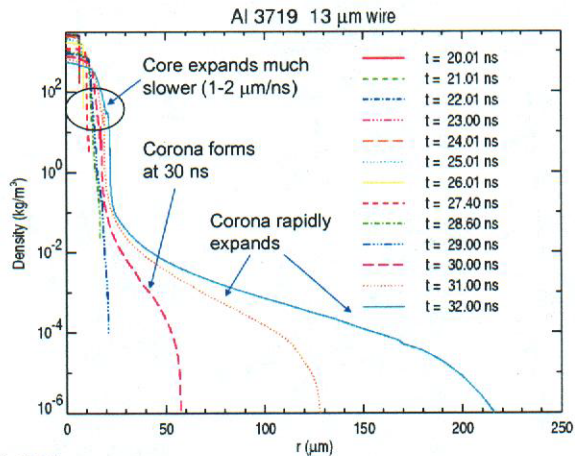
The Inner Edge of the High-Temperature Corona Provides an Alternate Evaluation of the Core Diameter



The thermal criterion is a simple one-step evaluation (possible only for the simulation); and after 250 ns, yields a constant-velocity core expansion similar to the experiment.



Sequential Snapshots of Radial Density Profiles Clearly Show the Corona Formation



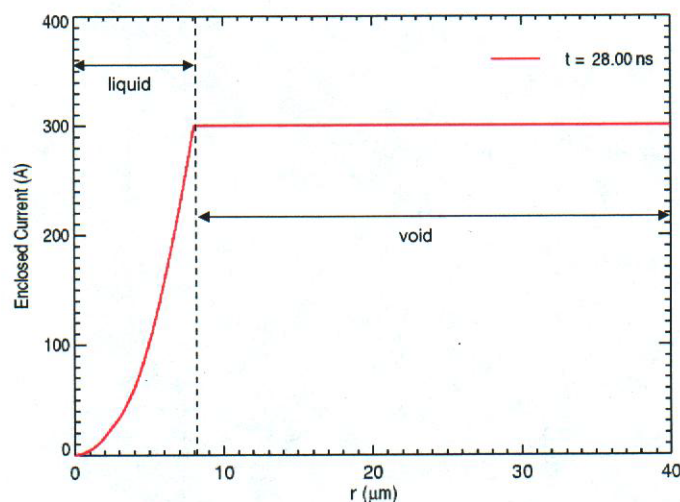
ALEGRA's "void" treatment allows a highly resolved view of the hot, low-density corona plasma in an exploding wire.

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Snapshots of the Radial Profiles of Enclosed Current Illustrate the Stages of Corona Formation

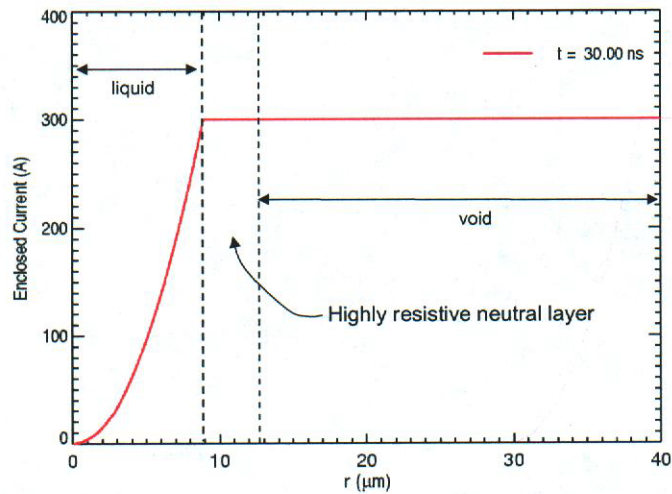


Stage 1: Pre-Corona

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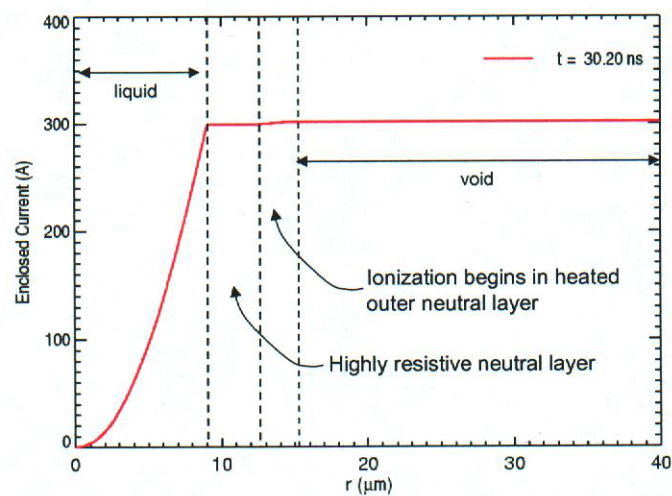
Stage 2: Neutral Gas Layer Evolves



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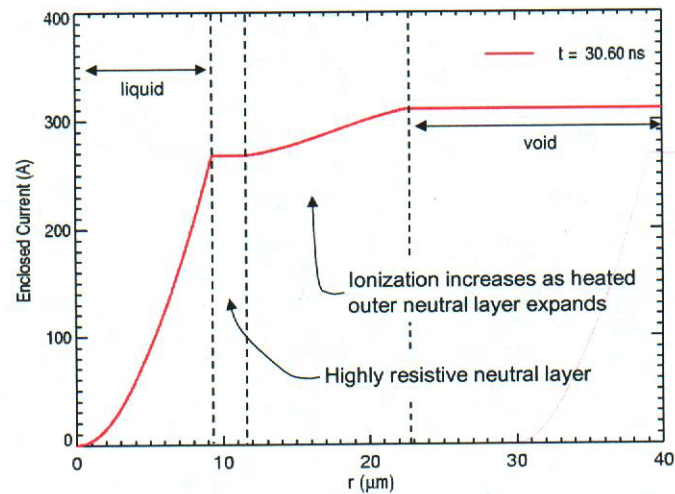
Stage 3: Ionization Begins Due to Ohmic Heating of Resistive Layer



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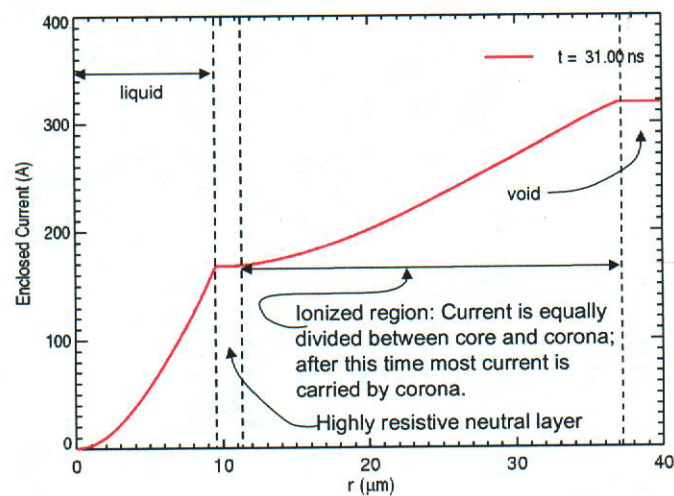
Stage 4: Conductivity of Outer Layer Increases



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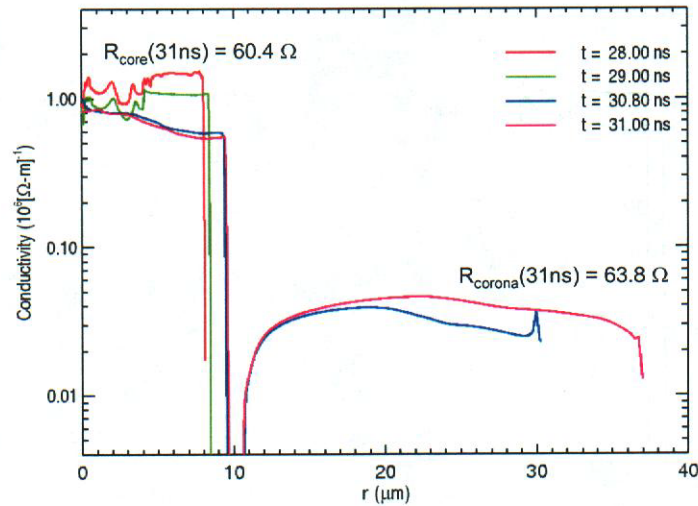
Stage 5: Corona State Fully Established



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Electrical Conductivity Profiles (with LMD-DFT Model)

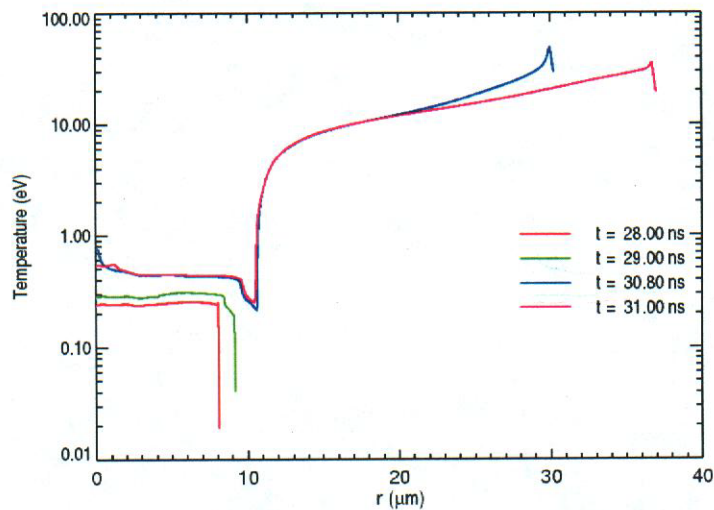


13 mm Al
EOS 3711



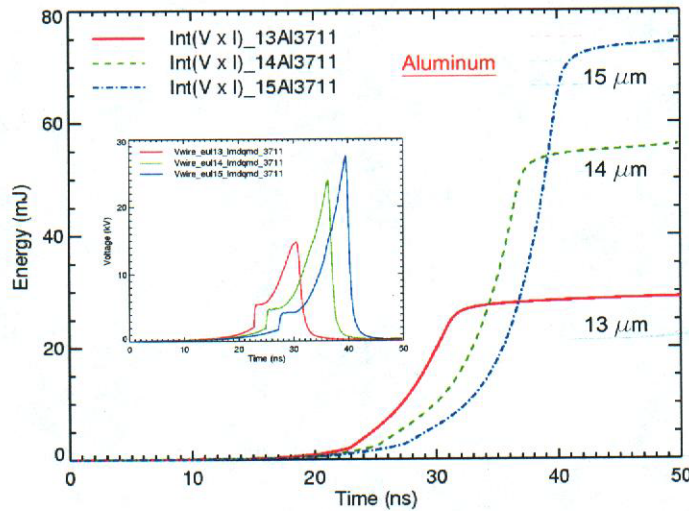
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Temperature Profiles (Comparable to Mean Charge State Profiles)

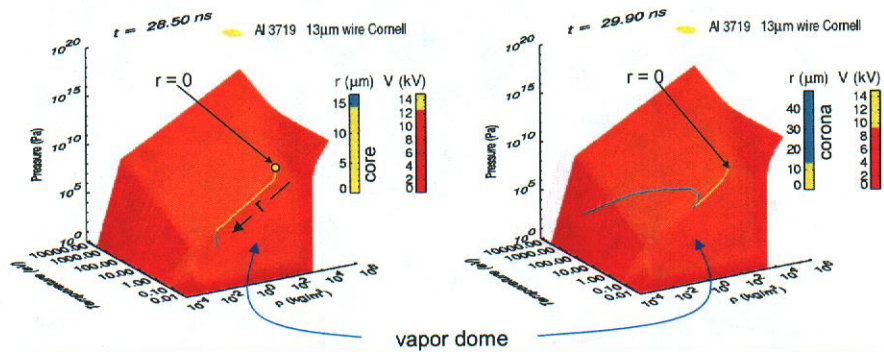


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Deposited Energy Comparison for Different Diameters



Parametric Plots of Wires in Phase Space Help Us See the Relationship Between EOS and Exploding Wire Dynamics

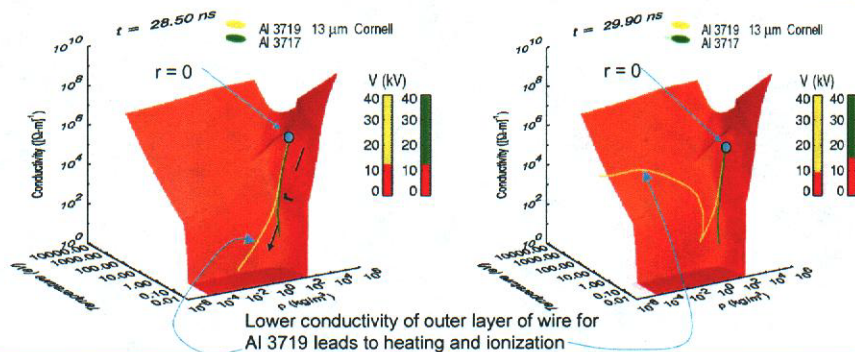


As the wire approaches the critical point (near $r=0$ point above: highest T and P where distinct liquid and vapor phases coexist), wire expands along vapor side into p -T region where conductivity is low and wire Ohmically heats and ionizes, forming corona.



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Simulations of an Exploding Wire Help Us Learn What EOS Features are Crucial for Corona Formation



EOS and Conductivity are nonlinearly coupled, so Corona formation is quite sensitive to the details of the EOS. Here the wire state from ALEGRA is displayed on the electrical conductivity surface to compare wire states from [yellow] EOS Al 3719 (vapor dome with Maxwell constructions) and [green] Al 3717 (Van der Waal loops).



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Advances We Are Making in EOS and Electron Transport Have Enabled Accurate Exploding Wire Simulations

- Simulations of a single exploding wire show strong dependence on detailed structure of electrical conductivity and EOS.
- ALEGRA and MACH simulations that use the recent L-M-D electron transport model and EOS with vapor dome and Maxwell constructions yield wire voltage in reasonable agreement with experiment.
 - timing is correct
 - voltage collapse (corona formation) resolved
 - no *ad hoc* surface conditions invoked; only pure Al considered
- Remaining discrepancy in voltage is partially related to inadequate solid binding energy in EOS and inaccurate specific heat. We are developing improved EOS tables. Refinements of L-M-D near solid density are also in progress.



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Acknowledgements



- Programmatic support: Rick Spielman, Tom Mehlhorn
- ALEGRA development: Thomas Haill, and ALEGRA Team
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extras



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